



# **Fiber-detector subsystem loss comparison for a ground-based photon-counting optical receiver**

**Free-Space Laser Communications XXXV**

**Session 7: Ground Transceiver Technologies II**

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# Introduction



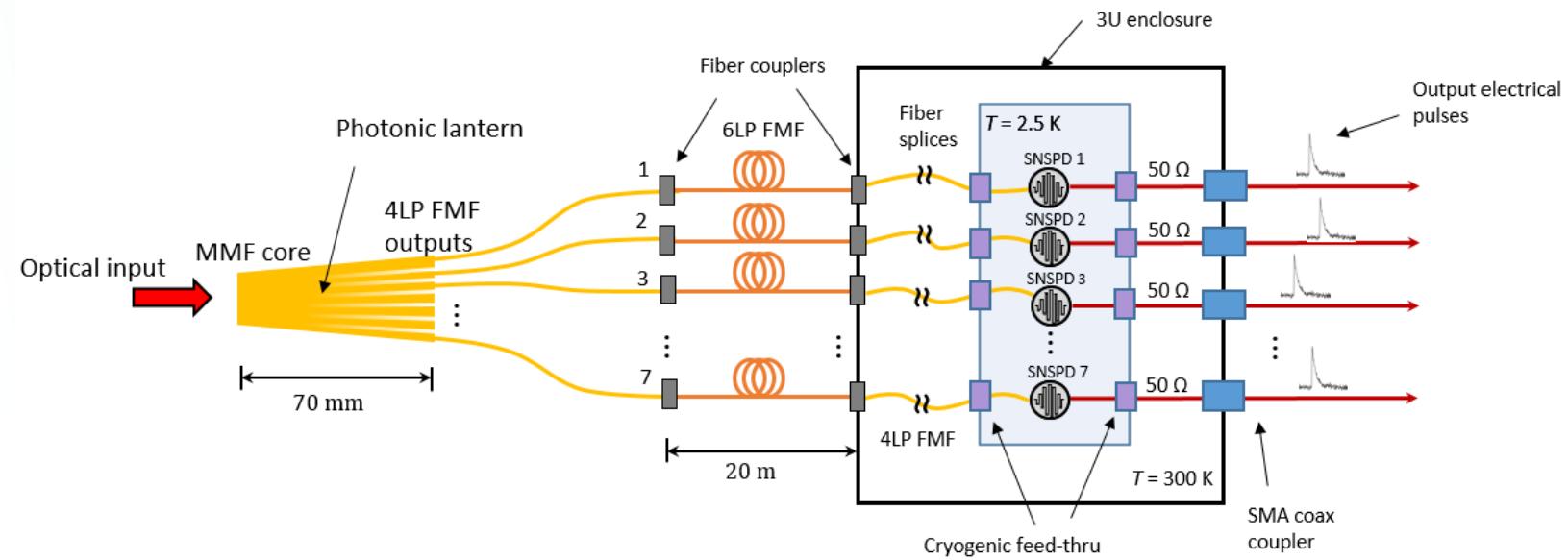
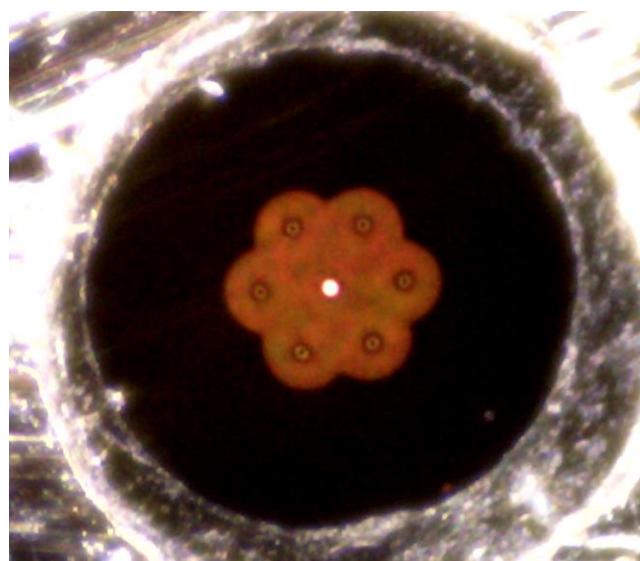
- NASA Glenn is building a photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard
- **Goals:**
  - Utilize commercial off the shelf (COTS) components
  - Demonstrate with O2O at the NASA Goddard Low-Cost Optical Terminal (LCOT) ground station
  - Transfer technology to commercial company
- **Receiver subsystems are:**
  - Fiber interconnect, from telescope to detectors
  - COTS superconducting nanowire single photon detectors (SNSPDs)
  - FPGA on COTS development platform for real-time processing
- **Two receiver concepts:**
  - Photonic lantern with 1 multi-mode input and 7 few mode fiber (FMF) outputs to 7 single-element COTS SNSPDs
  - A single FMF to a COTS 16-element SNSPD array
- **Need to fully characterize system losses**

# Photonic Lantern + 7 Single Element Detectors



## Photonic Lantern:

- **FMFs:**
  - 20  $\mu\text{m}$  graded-index core
  - 4LP, 6-mode
- **MMF input:**
  - 55  $\mu\text{m}$
  - 42 total modes



# FMF + 16-Channel SNSPD Array



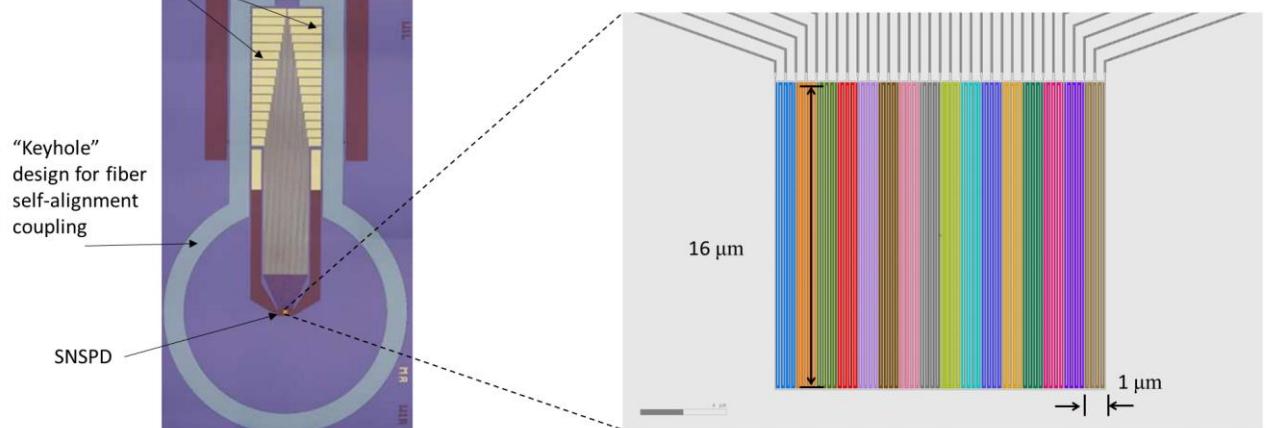
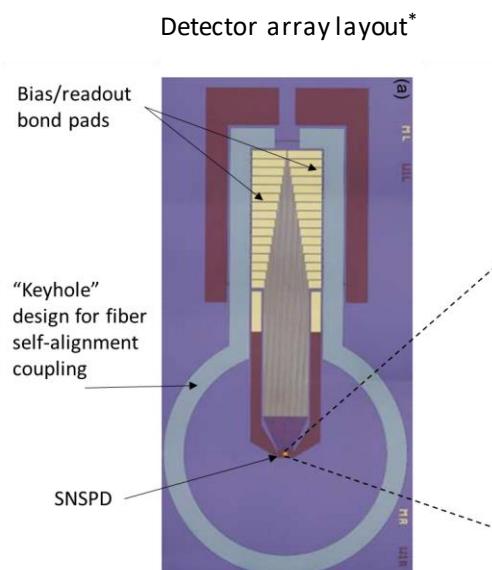
## FMF #1 (coupled to SNSPD array):

- 20  $\mu\text{m}$  graded-index core
- 4 LP, 6-modes

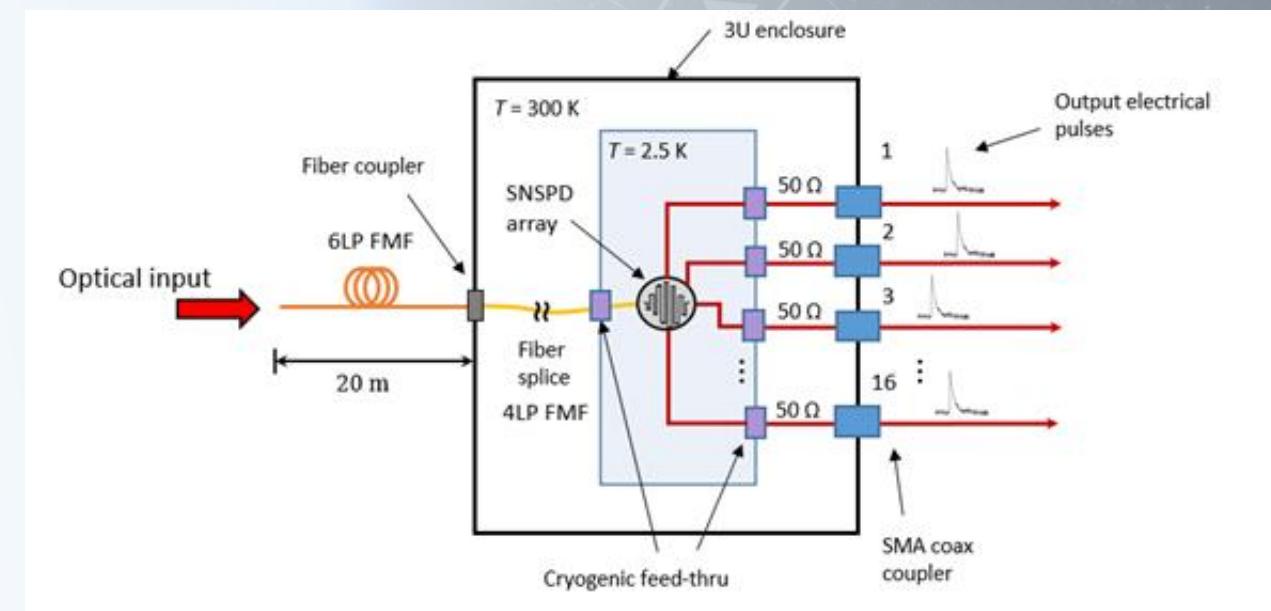


## FMF #2 (20 m system input):

- 25  $\mu\text{m}$  graded-index core
- 6 LP, 10-modes

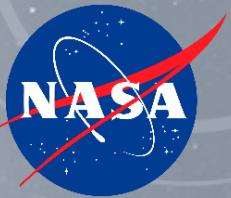


Layout of the SNSPD linear array active area, with each individual element color-coded



\*Rambo, T. M., Conover, A. R., and Miller, A. J., "16-element superconducting nanowire single-photon detector for gigahertz counting at 1550-nm," (2021). <https://arxiv.org/abs/2103.14086>

# SNSPD Characteristics



## Single-Element Detector

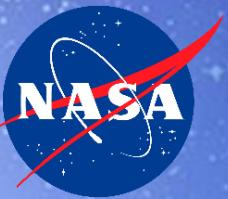
Parameter	Value
Efficiency	≈ 80 - 83% max
Dark count rate	< 5 kcps
Polarization loss	1.2 dB
Reset time	15 - 18 ns
Pulse rising edge	≈ 850 ps
Pulse amplitude	600 – 800 mV
Blocking loss*	< 1 dB @ 100 M-ph/s
Count rate (3 dB)*	≈ 160 Mcps @ 400 M-ph/s
Jitter (FWHM)	≈ 60 – 80 ps
Channel skew	< 500 ps

\* Aggregate for 7 detectors

## 16-Channel Array

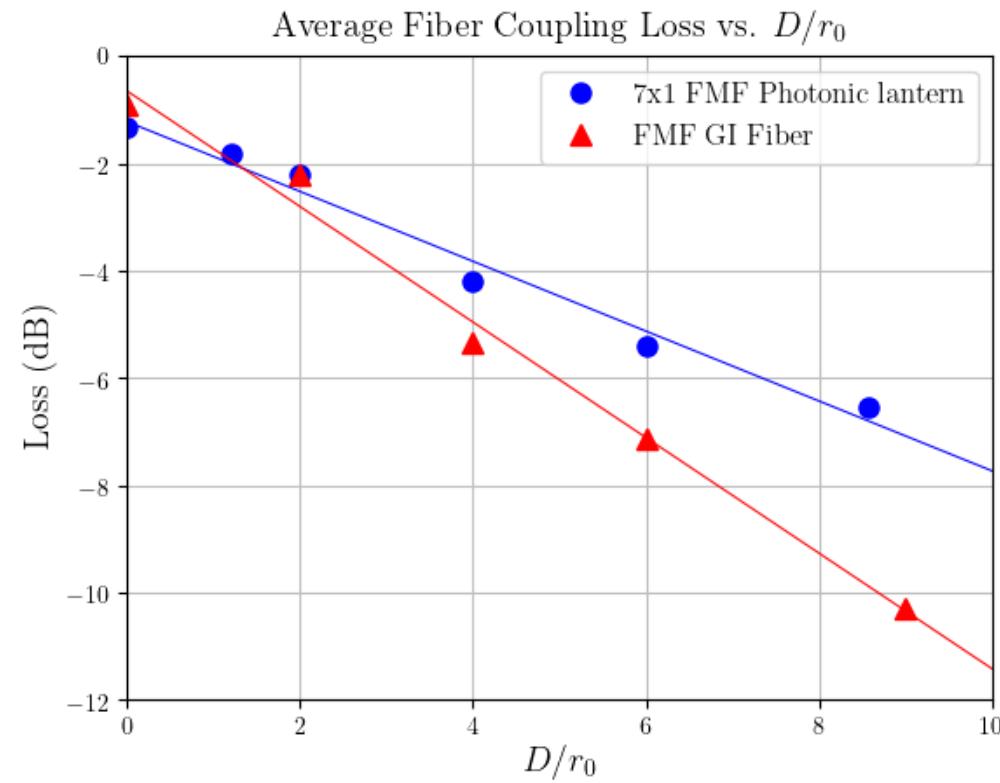
Parameter	Value
Efficiency	≈ 83% max
Dark count rate	3 - 10 kcps
Polarization loss	1.35 dB
Reset time	5 - 8 ns
Pulse rising edge	≈ 500 ps
Pulse amplitude	240 – 300 mV
Blocking loss	< 1 dB @ 300 M-ph/s
Count rate (3 dB)	≈ 500 Mcps @ 1 G-ph/s
Jitter (FWHM)	75 – 95 ps
Channel skew	< 150 ps
Crosstalk probability	< 0.002%

# Sources of Loss



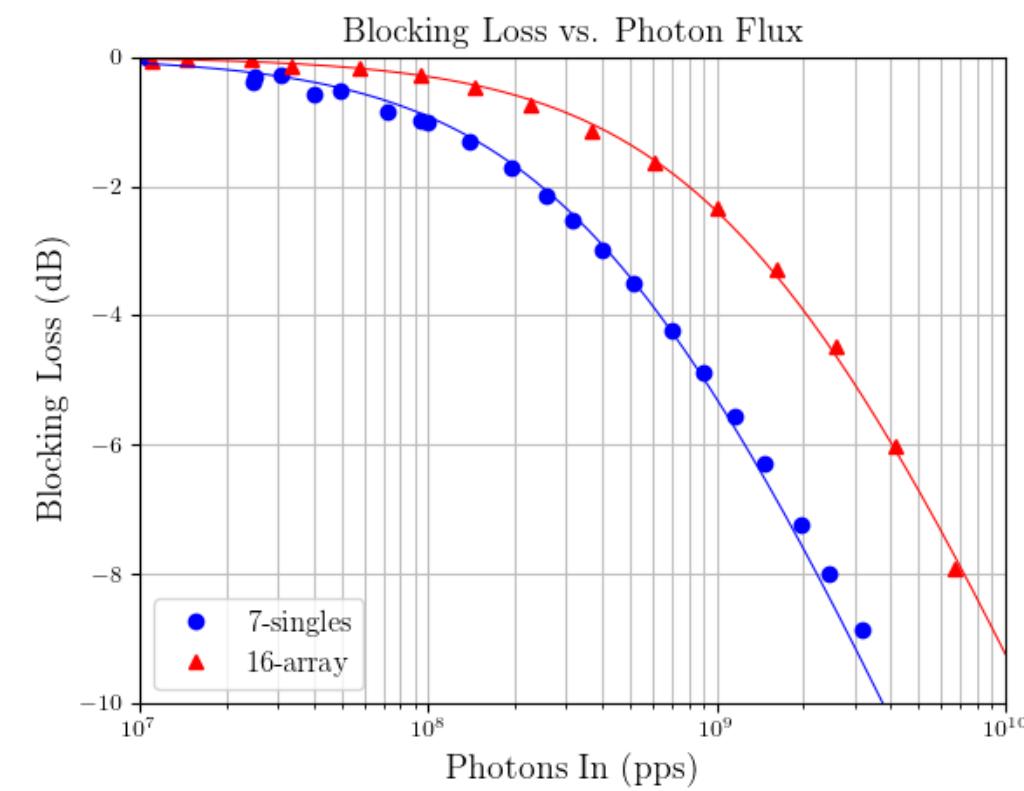
## Fiber interconnect:

- Coupling under atmospheric turbulence
- Control of distribution to detectors

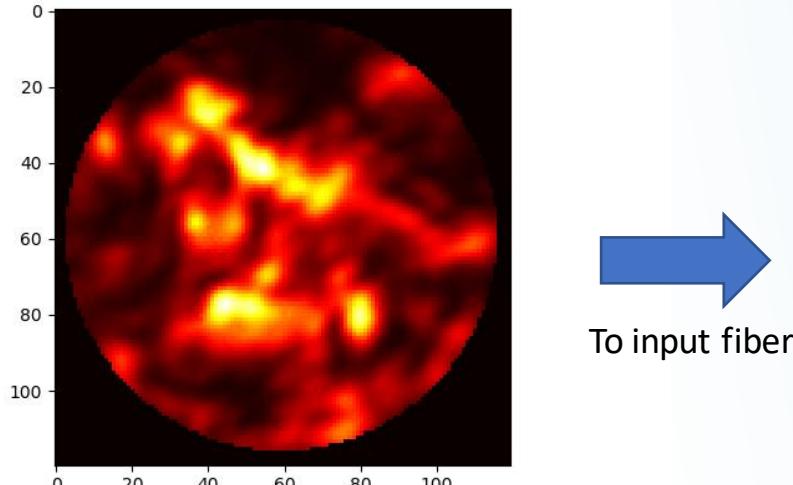


## Single-photon detectors:

- Detection efficiency
- Reset time limits count rates
- Depends on input rate (power)

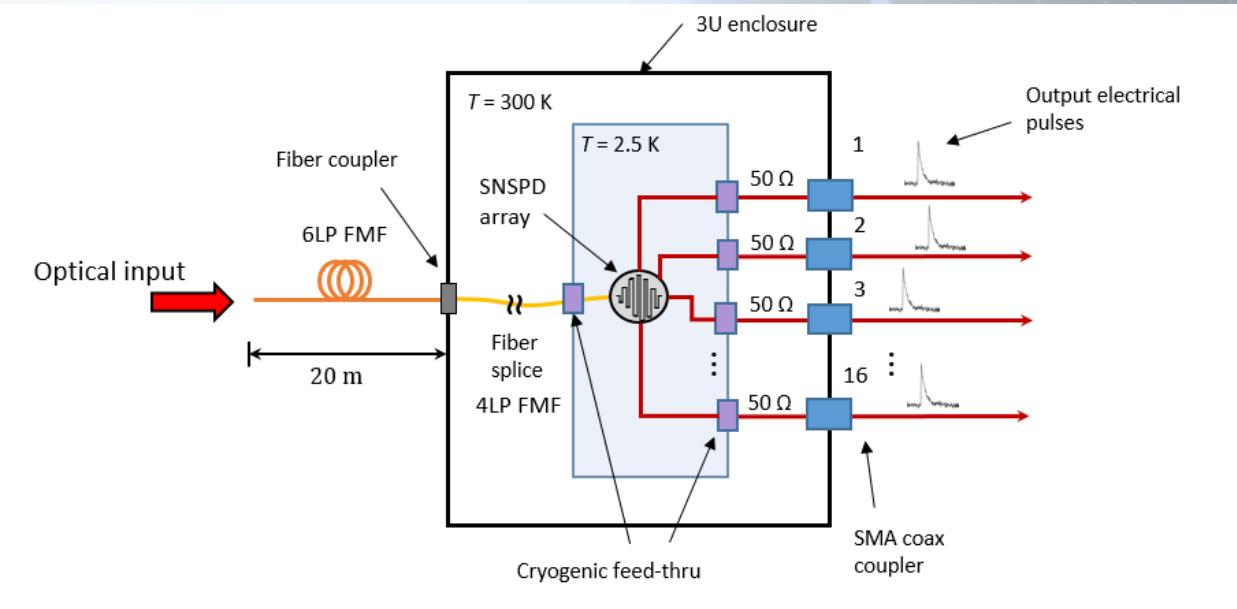


# SNSPD Array Count Spatial Distribution



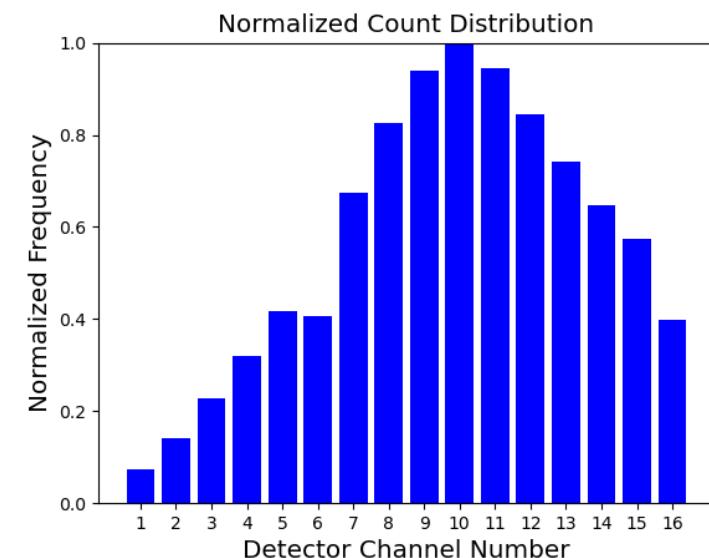
To input fiber

Emulated turbulence intensity profile from  
Arbitrary Light Field Generator (ALF-G)



- Emulated wavefront from the ALF-G couples to input 25/20- $\mu\text{m}$  FMF which is coupled to the 16- $\mu\text{m}$  SNSPD array

**Linear SNSPD array layout provides 1-D spatial information.  
Distributions are in general, non-uniform.**

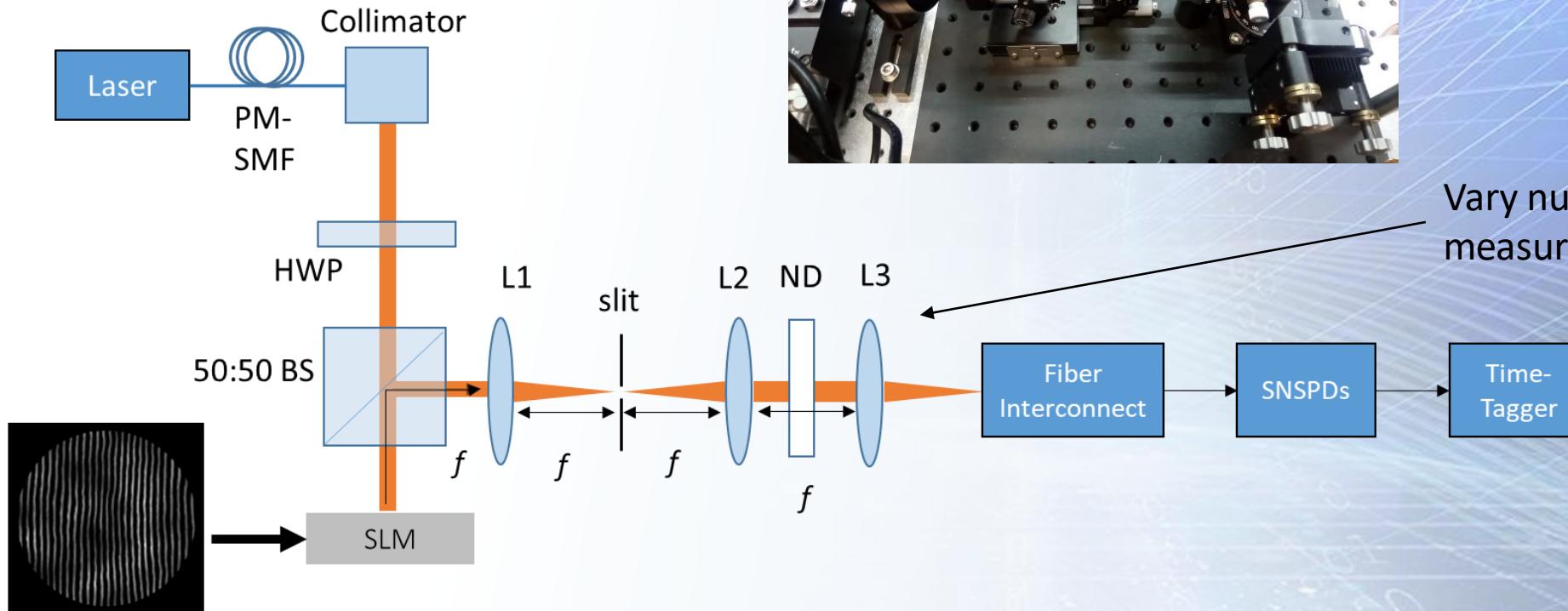


Output average count distribution for emulated wavefronts

# Arbitrary Light Field Generator (ALF-G)

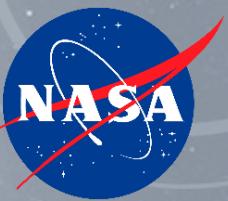


Simulated 2D beam profiles (phase and intensity) are recreated in the lab by modulating the beam via a complex amplitude phase hologram written to the SLM.

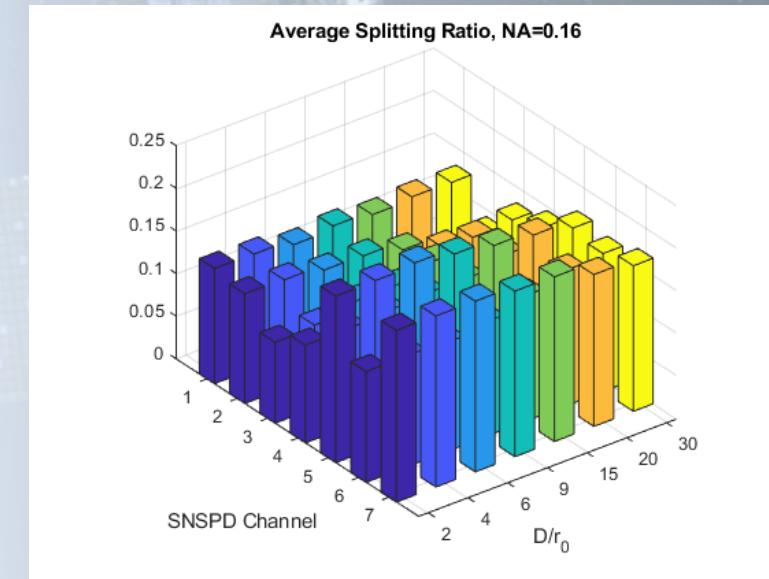
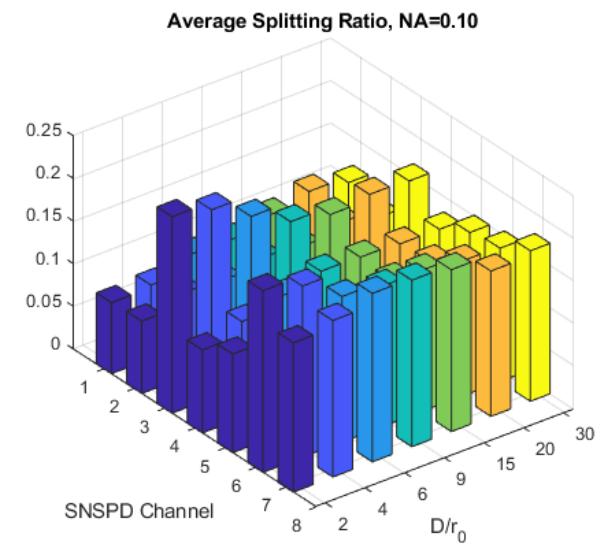
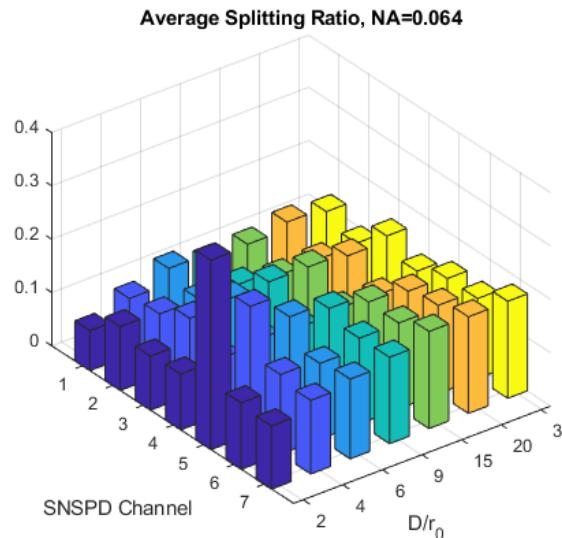


**Hologram of beam with emulated atmosphere**

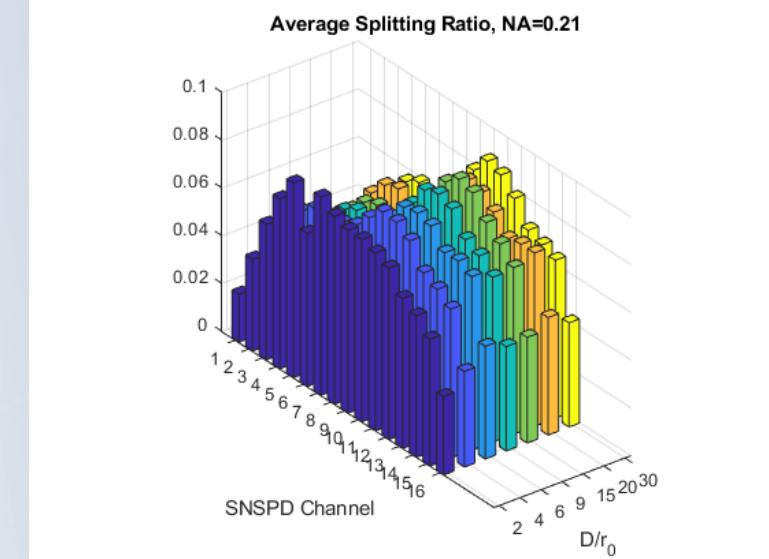
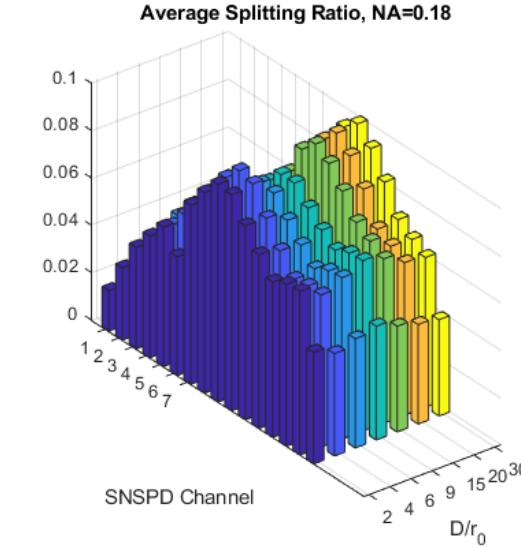
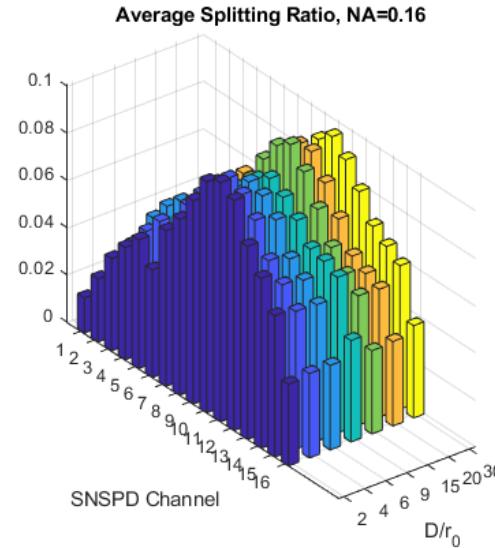
# Average Count Rate Distributions



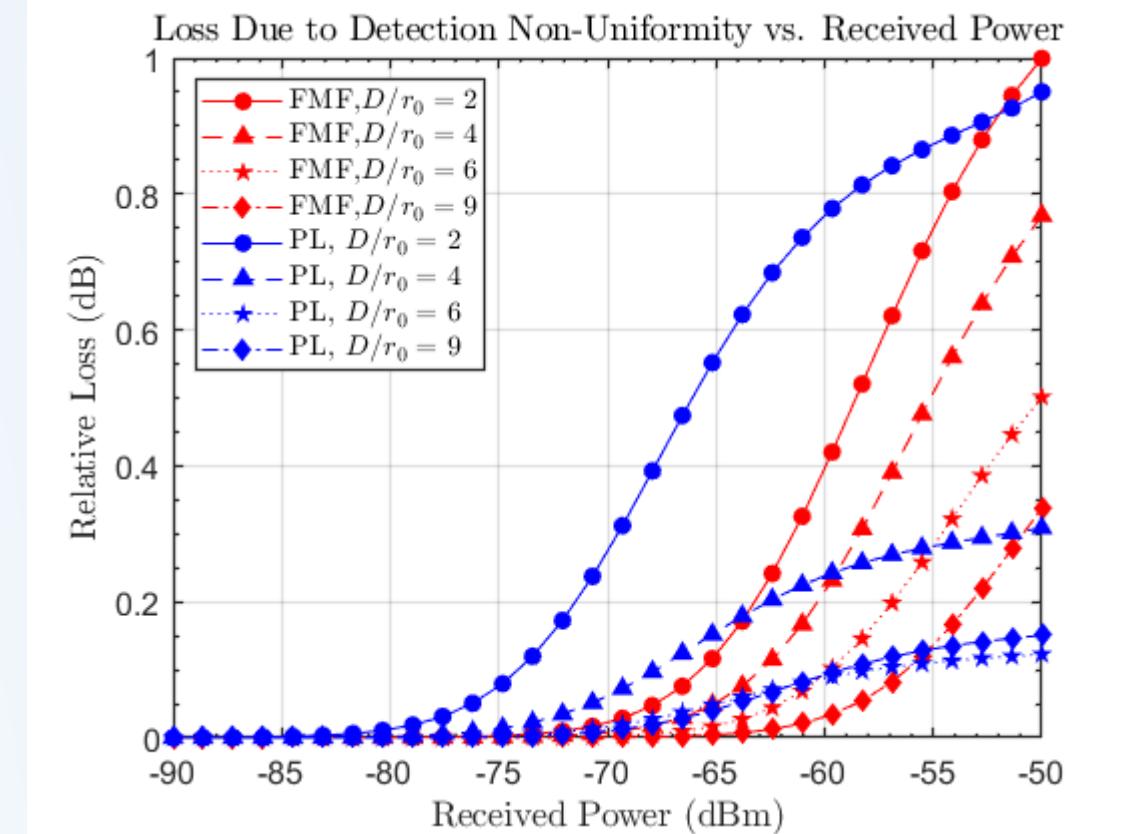
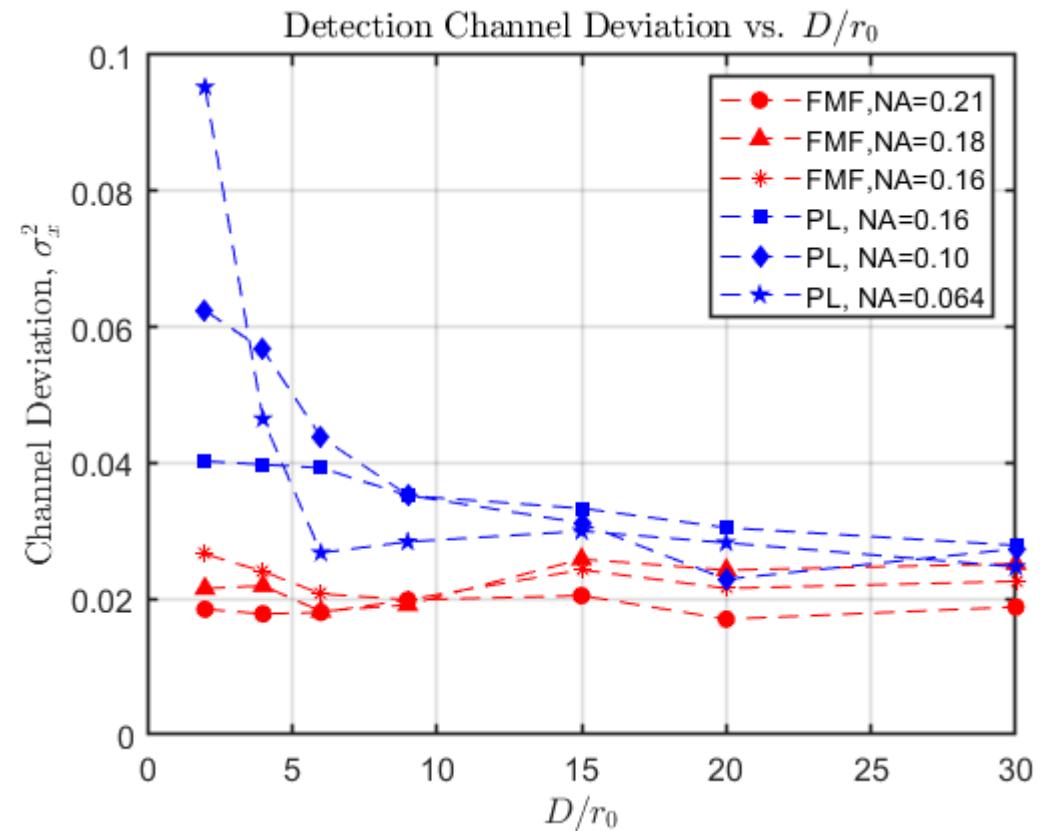
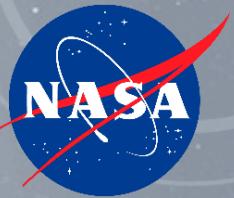
## Photonic lantern



## FMF

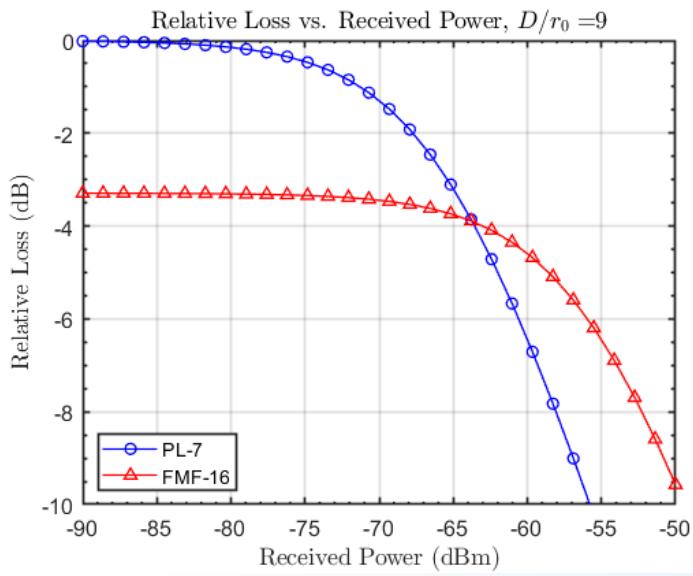
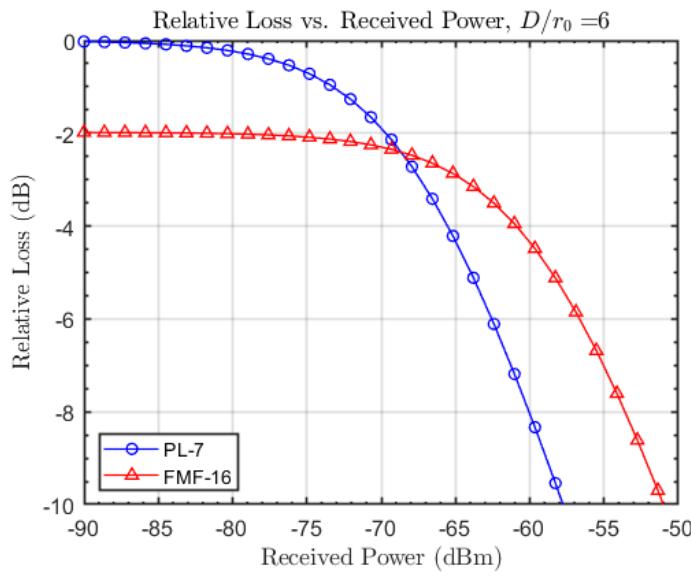
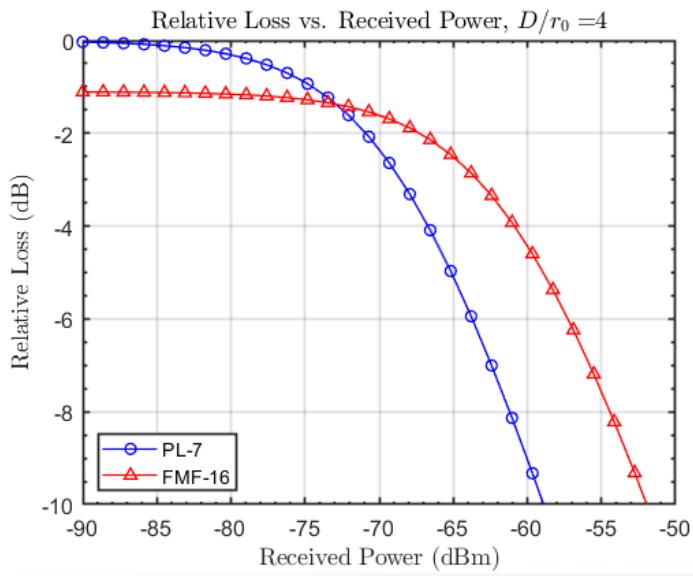
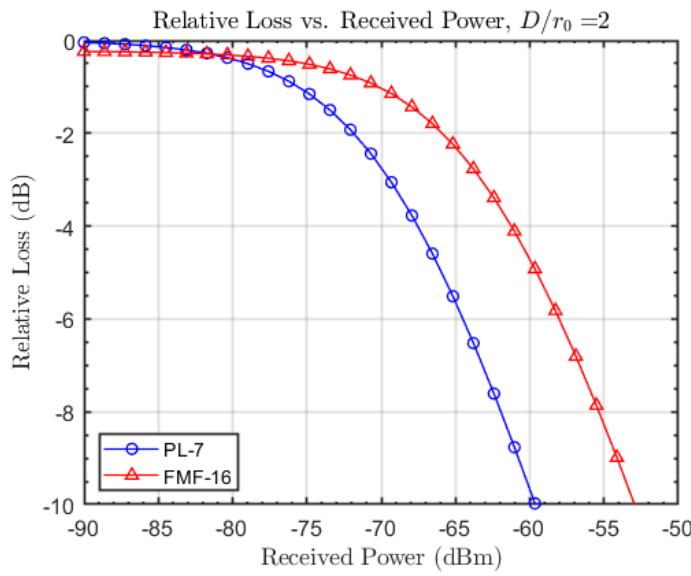
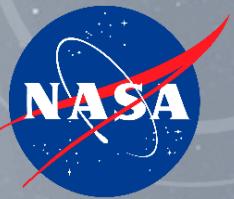


# Added Loss From Non-Uniform Distribution



Additional flux dependent loss due to the non-uniformly distributed incident light is less than about 1 dB for all  $D/r_0$

# Loss Comparison



$D/r_0$	Relative Loss (dB)	$P_{RX}$ (dBm)
2	0.20	-81.31
4	1.08	-72.82
6	1.96	-68.78
9	3.28	-63.53

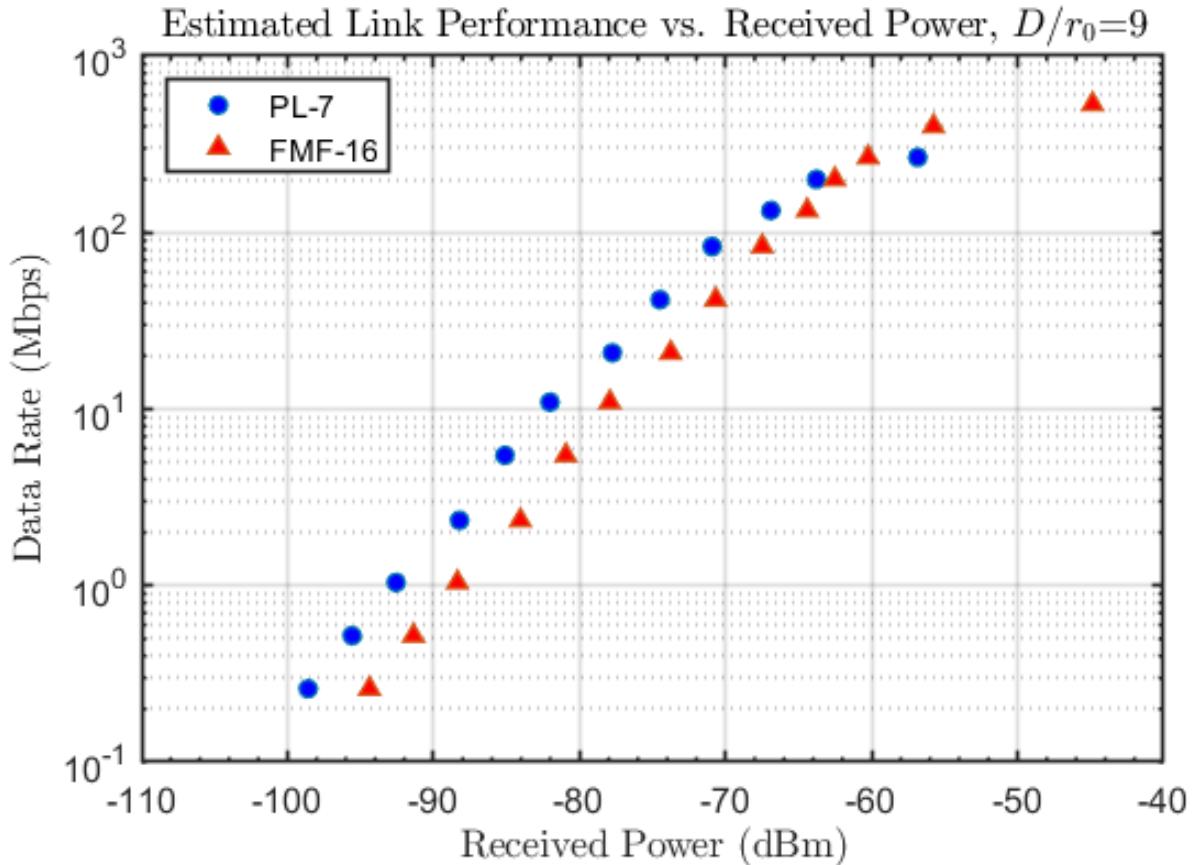
- Combined coupling loss, blocking loss, and input distribution effects over a range of input power
- FMF/SNSPD array system has more loss at lower received power and higher  $D/r_0$  due to coupling
- Photonic lantern/single SNSPDs system has more loss at higher input powers due to detector count rate limitations
- There is a cross-over input power where relative coupling loss balances detector blocking losses

# Estimated Link Performance



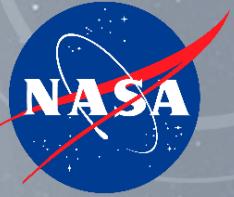
## Parameters:

- **PPM order**  
 $M = \{4, 8, 16, 32, 64, 128, 256\}$
- **Code rate**  
 $CR = \{1/3, 1/2, 2/3\}$
- **Slot width**  
 $T_s = \{0.5, 1, 2, 4, 8, 16, 32\} \text{ ns}$
- **Implementation loss:**
  - 0.3 for PL-single element SNSPDs
  - 1.2 for FMF-SNSPD array
- **Assumes BER  $\leq 10^{-6}$**
- **Margin  $\geq 2 \text{ dB}$**
- **230 kbps – 533 Mbps**



Both systems show feasibility to achieve data rates into the 100s Mbps. The photonic lantern-based system outperforms the FMF/array system for lower data rates/input power.

# Summary



- We have characterized the main loss mechanisms for two fiber-detector subsystems as part of a photon-counting optical receiver based (mostly) on commercially available components
- Losses due to coupling, blocking, and non-uniform signal splitting were quantified, for a range of input power and various  $D/r_0$
- With optimal coupling, the receiver concept based on a FMF photonic lantern with 7 single-element SNSPDs has lower total losses for lower data rates and input powers
- For rates above  $\sim 200$  Mbps the single FMF-SNSPD array system outperforms and can potentially achieve data rates up to 533 Mbps



# Thank You!

[www.nasa.gov/SCaN](http://www.nasa.gov/SCaN)